PhD Dissertation Research Proposal

Military Hybrid Vehicle Optimization and Control *

Denise M. Rizzo

Mechanical Engineering-Engineering Mechanics

Michigan Technological University

August 14, 2012

*Unclassified. Distribution Statement A. Approved for public release.

Abstract

Hybrid vehicles are increasingly common in the passenger car marketplace and in commercial applications such as delivery trucks and transit busses. These hybrids are justifiable due to their increased fuel efficiency and the associated cost benefit. It is remarkable, then, that there are no deployed military hybrid vehicles, when fuel costs as high as $100 per liter are common in the battlefield. An absence of military hybrid vehicles is not due to a lack of investment in research and development, but rather because applying hybrid vehicle architectures in a classical sense to a military application has challenges that make fielding such a vehicle prohibitive. These challenges include inconsistent duty cycles, unique vehicle requirements and the absence of holistic view of energy. The proposed research addresses these challenges while illuminating the comprehensive benefits of military hybrid vehicles with respect to operational energy, which includes propulsion power, electric power for government furnished equipment (GFE), silent watch capability, and vehicle-to-grid (V2G) mobile energy exchange and storage. By treating a military vehicle as a microgrid, a methodology for developing optimal battery state of charge (SOC) profiles for military duty cycles will be developed. A proof of concept will be presented along with the detailed steps necessary to extend this work into a military environment, including reduced order optimization and sensitivity analysis. Finally, the impact and timeline of this doctoral research project will be explained.*

1 Introduction

With ever increasing emission and fuel economy requirements in the U.S., Europe and Asia, most of the passenger car (defined as 3,850 kg or less) Original Equipment Manufacturers (OEMs) have conducted extensive research on various types of hybrid vehicles. The literature illustrates not only research, but includes product development; most of the OEMs in Europe and the Americas have a hybrid model in the marketplace or will introduce one in the near future [1]. Hybrid powertrain components consisting of power electronics and electric motor drives have established themselves as a means of improving the energy efficiency of passenger cars [1]. Additionally, there has been significant progress in the development of hybrid transit busses worldwide [2], which have also shown that energy savings can be realized with hybrid powertrains. Hybrids have also been extended to delivery trucks and garbage trucks, which have a similar application that utilizes the same type of urban drive cycle.

Militaries worldwide are also interested in realizing the potential energy savings associated with hybrid vehicles. "Fossil fuel accounts for 30 to 80 percent of the load in convoys into Afghanistan, bringing costs as well as risk. While the military buys gas for just over \$1 a gallon, getting that gallon to some forward operating bases costs \$400," according to Gen. James T. Conway, the commandant of the U.S. Marine Corps [3]. In fact, the U.S. Army has been researching hybrid vehicles since 1943 [4]. However, from observing the literature, it appears that the U.S. and other countries are far away from realizing a hybrid ground vehicle.

There are very few, if any, military hybrid hardware related papers, and many of the papers overlook some of the basic requirements of military ground vehicles, such as 60% grade ability and fording. The lack of literature related to European and Asian military vehicles suggests that armies worldwide are also facing the challenge of fielding a hybrid military vehicle. Furthermore, a standard or universally accepted military duty cycle for measuring fuel economy does not exist nor does the research focus on a particular technology. This could be for the following reasons:

1. Military ground vehicle researchers do not publish as readily as OEM researchers, due to lack of available data, test vehicles and proprietary information.

2. The challenge of a military application is much greater due to the ever increasing and mutating threats that translate into continually changing vehicle requirements.

3. The life cycle of military vehicles is much different than that of passenger vehicles and not enough development has been completed to understand the long-term reliability and maintainability of hybrid components.
4. The off-highway mobility requirements, i.e. soft soil mobility, present a unique challenge and off-highway production hybrid vehicles are only recently starting to emerge in the construction equipment sector.

It is important to note that there are other potential payoffs associated with military hybrid vehicles. The first benefit is the ability to idle and possibly move without the noise and thermal signatures of an internal combustion engine [4]. Another benefit is the increased available onboard electrical power; not only can a hybrid system, such as an engine with an integrated starter generator, provide more electrical power than the typical alternator, but this power can be converted, conditioned and delivered in any form to and from any load. Some examples included charging the soldier's battery powered equipment or delivering power back into an electrical grid. Additionally, new military vehicles are demanding an excess of 50kW of electrical power [5], which can only be provided with an advanced onboard power unit or a hybrid system. Quantifying these capabilities from an operational energy standpoint could help governments understand the benefits of military hybrid vehicles.

Electric power delivery is especially important to the U.S. Army, because their reliance on electrical power is greater than ever and the loss of battlefield electricity imposes a significant loss of capability and operational performance [6]. To ensure power and energy security, as well as reduce overall energy use, the concept of a microgrid has been introduced [7, 8]. A microgrid is defined as an aggregation of consumers and sources operating as a single system. It can connect to other grids or be operated as an island. Additionally, emerging vehicle-to-grid (V2G) technology has been show to have the ability to support the microgrid as a source, but also a storage device for excess energy [9]. From a military standpoint, there is also an added benefit of temporary connectivity or network capability, which could be useful in a temporary peacekeeping or military operation.

To date, the V2G capability that comes along with a military hybrid has lacked quantifiable value, making it difficult to perform a cost / benefit analysis when trade studies are conducted. Additionally, there are many challenges related to controls and optimization for hybrid vehicles serving in a V2G capacity that need to be explored. Therefore, this proposal will outline military hybrid research to date with special attention paid to duty cycles and constraints. It will explain the challenges and reasoning of why a military hybrid vehicle has yet to be fielded. It will introduce the dissertation research objective of understanding the benefit of a military hybrid vehicle from an operational energy perspective allowing the benefit of a military hybrid vehicle to be understood.

The scope of this proposal includes introducing the concept of regarding a military hybrid vehicle as a microgrid and utilizing battery state of charge (SOC) optimization to minimize energy use in a military scenario. A proof of concept will be explained. The research plan to verify this concept military environment, which includes reduced order optimization and drive cycle sensitivity, will be explained. Lastly, the paper will detailed the impact, timeline and conclusion.

2 Research Background

To explore the concept of treating a military hybrid vehicle as a microgrid and understand holistic energy use, it is important to review the work that has been done related to military hybrid vehicles to date. This section will therefore explore a survey of work on military hybrid vehicle energy use with special attention paid to drive cycles and constraints.

For fifty years, the U.S. military has been considering the use of electric drive technology [10]. To understand the performance of this technology, the Hybrid-Electric Vehicle Experimentation and Assessment (HEVEA) program was initiated in 2005 [10]. The goals of this program were to understand how hybrids performed in a military environment, establish a test procedure for evaluating their performance and create a validated simulation tool for evaluating system-level performance [10, 11]. With the introduction of the Future Combat Systems (FCS) program, a series of conference papers were published by various OEMs to show hybridization capability on current vehicles using OEM specific hardware [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. Additionally, the commercial sector has shown success with hybrid systems for heavy duty vehicles that have a known drive cycle, such as city busses and delivery trucks.

Currently, the three technology demonstrators for the U.S. Army's Joint Light Tactical Vehicle (JLTV) all have Integrated Starter Generators (ISGs), which are not used for propulsion, but could be expanded into mild hybrid capability with the addition of a clutch connecting the generator to the transmission and additional energy storage [23, 24]. Additionally, the U.S. Army's Fuel Economy Demonstrator (FED) program is creating two demonstrator vehicles: one will have an ISG only and one will be a parallel electric hybrid [25, 26, 27, 28].

2.1 Military Application of Hybrid Systems

While there are significant challenges to fielding a military hybrid vehicle, there is also significant opportunity to reduce fuel consumption and provide additional capabilities to the soldier.

2.1.1 Challenges

There has been years of work on U.S. military hybrids. However, there has not been a military HEV fielded to date. A paper published in 2009 explains in detail the challenges that military vehicles face [4]. In summary, the vehicle performance requirements such as 60% grade ability, speed on grade, cooling and soft soil mobility add challenges that could diminish the efficiency gains seen by a hybrid vehicle. In addition, their reliability and maintainability is unknown for the lifecycle of a military vehicle. Lastly, the continuously changing threat impedes engineers from understanding the duty cycle and use of the vehicle. However, as technology advances and hybrids become mainstream for commercial applications, including some heavy duty vehicles such as busses and delivery trucks, it appears that these technologies could be leveraged to eventually field hybrid military vehicles.

2.1.2 Opportunity

It is generally accepted that hybrids can provide improved fuel economy. In fact, a study conducted in 1999 concluded that by just considering an engine fuel map and eliminating the inefficiencies associated with idling, vehicle braking and low engine speed part load efficiency, notable improvements could be realized as shown in Table 1 [29]. Note that vehicle classes are defined by gross vehicle weight (GVW), where: class III - 4,536-6,350kg, class IV - 6,351-7,257kg, class V - 7,258-8,84 kg, class VI - 8,846-11,793kg, class VII - 11,794-14,969kg, and class VIII - 14,970kg + [30]. While this work does not take into account component integration or optimal controls, it does show the potential for medium and heavy duty vehicles. Another study by Stodolsky et al. [31] showed that class III-IV trucks can obtain an average of 93% fuel economy gains over a number of urban / city cycles while class VI-VII trucks can obtain an average of 71% over the same cycles. These two papers illustrate the promise of fuel economy improvements in heavy vehicles.

Table 1: Fuel savings for Class III and IV trucks predicted by the study of Reference [29].

Vehicle	Vehicle Class	Fuel Economy Improvement	Method
Ford E-Super Duty Truck	III	61%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)
GMC C-Series P-Chassis Truck	III	75%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)
Navistar 300 Series Bus	III	35%	Average over Central Business District (CBD), New York City Bus Cycle and Commute Phase Truck Cycle (COMM)

2.2 Vehicle and Powertrain Overview

This section will introduce military vehicles and the hybrid powertrain configurations used in literature.

2.2.1 Vehicles

While many different vehicles are used in worldwide operations, there are only three different military vehicles used for all of the publications: High Mobility Multi-purpose Wheeled Vehicle (HMMWV), shown in Figure 1, Family Medium Tactical Vehicle (FMTV), shown in Figure 2, and Heavy Mobility Expanded Tactical Truck (HEMMTT), shown in Figure 3. However, these three vehicles span a wide range of weights from 4,536 kg to 14,970 +kg, indicative of class III through class VII vehicles. Furthermore, information and data related to these vehicles is readily available.

Figure 1: HMMWV

Figure 2: FMTV

Figure 3: HEMMTT

2.2.2 Parallel Powertrain

A parallel hybrid powertrain is a configuration where two power sources, typically an internal combustion engine and an electric motor, propel the vehicle. This system is described by the term "parallel" because the power to move the vehicle can come from either or both of the sources at any time. A detailed description of the different powertrain versions are explained in references [32, 33, 34, 35]. Note that a "series-parallel" hybrid is used to describe a parallel hybrid where one source can be completely uncoupled from the second source. That first source, typically and internal combustion engine, can be used as in a series hybrid, which is explained in the next section.

2.2.3 Series Powertrain

A series powertrain is where a single power source propels the vehicle, but that source receives its power from additional sources. Typically, electric motors propel the vehicle using power supplied by an internal combustion engine powered generator/energy storage system. This system is called a "series hybrid" because propulsion power is transferred in a serial fashion from one source to the next; power is not blended from multiple sources as in a parallel hybrid. A detailed description can be found in references [32, 33, 34, 35].

2.3 Drive Cycle Overview

To determine fuel economy, it is necessary to test or simulate a vehicle over a specified drive cycle. A review of the literature showed that many different drive cycles were being used to evaluate vehicle performance. These cycles can be divided into two categories: (1) time dependent speed profiles, shown in Figure 4, usually defined by the federal government (EPA) [36], including the FTP 75 cycle, urban cycle and the highway cycle and (2) distance dependent grade or elevation profiles, shown in Figure 5, usually defined by the U.S. Army, including the Churchville cycle, Harford cycle and Munson cycle.

In general, hybrid vehicle fuel savings are best realized when the vehicle undergoes frequent speed or load changes. A qualitative examination of Figures 4 and 5 shows that the FTP75, Federal Urban, Churchville and Hartford cycles all have significant

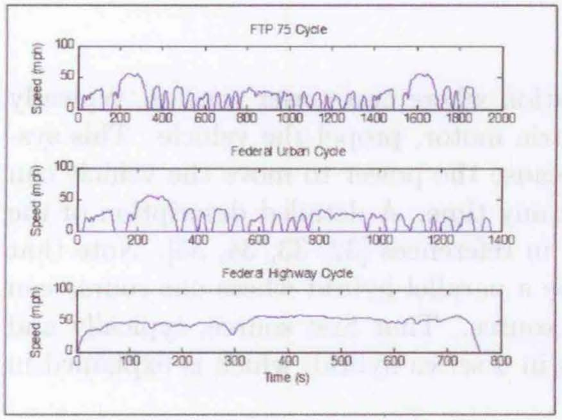

Figure 4: Time dependent speed profiles

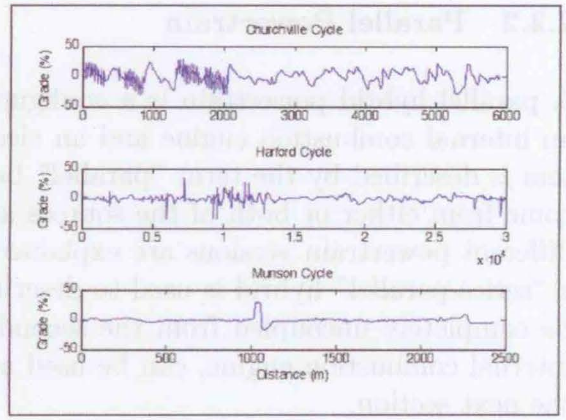

Figure 5: Distance dependent grade profiles

speed or load frequency content. Conversely, the Federal Highway and Munson cycles have very few speed or load changes.

2.4 Documented Fuel Economy Improvements

This section will explain influence of these different drive cycles on fuel economy.

2.4.1 Parallel Powertrain

For parallel hybrid configuration, a class III HMMWV can realize between 4.3-45.2% fuel economy improvement depending on technology and drive cycles, whereas the class VI and VII FMTV can realize between 2-32% and 7-15% respectively. Lastly, the class VIII HEMMTT only demonstrates an improvement between 0 - 2%. The results of these studies indicate that for parallel hybrid powertrains there exists more opportunity for fuel efficiency improvement in smaller class vehicles. A detailed list of fuel economy improvements along with methodology and technology can be found in [37].

2.4.2 Series Powertrain

For a series hybrid configuration, a HMMWV can realize between 7-68% fuel economy improvement depending on its technology and drive cycles, where the FMTV can realize between -5.9-30% and -1.5-19.2% for class VI and VII, respectively. The HEMMTT can demonstrate between 12.5-17.4% and 0-15.8% improvement for class VII and VIII, respectively. Last, a notional military bus (class VI) shows a 12.5%-19.1% improvement, again depending on drive cycle and technology. The series hybrid analysis, as with the parallel hybrid cases, demonstrates the greatest opportunity for efficiency improvement with lighter vehicles. However, the series hybrid shows more potential for improvement in the very large class VII-VIII vehicles than a parallel hybrid. A detailed list of fuel economy improvements along with methodology and technology can be found in [37].

2.4.3 Drive Cycle Impact

To further understand the effect of drive cycles, Figure 6 shows cycle versus percent fuel economy improvement for series, parallel and series-parallel combination for the class III HMMWV vehicle based on the results provided in references [38, 39, 40, 41, 42, 43, 44]. While the configuration and methods were different for each of the points on the plot, a general trend shows that the hybrid HMMWVs show more improvement on urban cycles, which is expected. Furthermore, vehicles tested on the Munson cycle show the least amount of fuel economy improvement, which is also anticipated since the Munson drive cycle is nearly a flat course without any stops as shown in Figure 5. Similar analysis for class VI, VII and VIII vehicles can be found in [37].

It is important to note that work has been done to develop a true military combat drive cycle and to understand operational fuel economy [45]. This study used a motion simulator with soldiers-in-the-loop facing military scenarios, such as a convoy escort mission, to determine typical speed and load profiles that could be used for a drive cycle. Based on the surveyed literature, these cycles have not been adopted by the community.

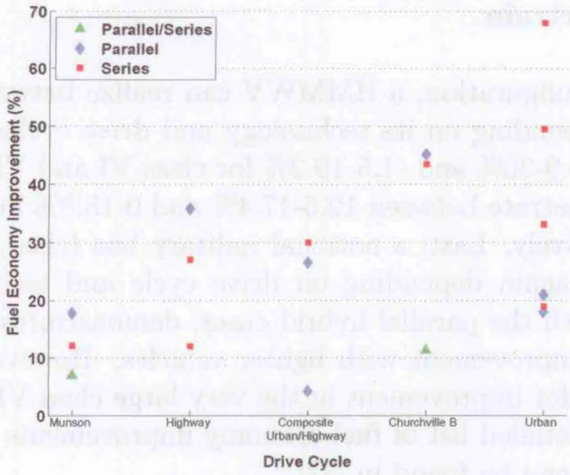

Figure 6: Cycle vs. fuel economy improvement for the HMMWV

In summary, the fuel economy improvement for military hybrid vehicles is highly dependent on the drive cycle used for the analysis. The existing literature shows a lack of a standard drive cycle for analysis, which makes it difficult to judge technologies and understand how the military can benefit from a hybrid vehicle. This is likely one of the reasons for the delay in fielding a military hybrid.

2.5 Constraint gaps

Military vehicles typically have clear requirements with regard to grade ability, acceleration levels and speed on grade. These military requirements will differ from commercial or passenger vehicles and for the different classes of vehicles; however, the literature shows that no standard set of requirements is being used even within a given weight class. Fuel economy will be adversely affected when trading off acceleration or grade performance; therefore, it is difficult to determine comparable fuel economy performance across studies using different requirements.

Table 2 summarizes the fuel economy improvements for the class III HMMWV over the urban cycle with different grade and performance requirements used for the analyses of the references [39, 40, 42, 43, 44]. For each of the studies, a different standard was used for grade or acceleration. In three cases, no information was given regarding these requirements. According to the Hybrid Electric HMMWV specification [46], the HMMWV at gross vehicle weight (GVW) shall:

Table 2: Summary of HMMWV urban cycle performance and requirements

Vehicle	Acceleration	Grade	Fuel Economy Improvement
Series Electrical	none	none	49.6%
Series Electrical	0-60 mph: 16.5s	3.2% grade @ 20mph	33.0%
Series Electrical	none	none	19.0%
Series Hydraulic	0-50mph: 10.8s	2% grade @ 55mph, 3% grade @ 45mph	68.0%
Parallel Electrical	0-60mph: 21.7s	0% grade @ 20mph	21.0%
Parallel Electrical	none	none	18.0%

- Be capable of starting and stopping on slopes up to and including 60%.
- Be capable of ascending a 5% grade at 55 mph.
- Accelerate from 0 to 30 mph within 9.0 seconds and from 0 to 50 mph within 24 seconds.

The analysis summarized by Dususin et al. [47] noted that 60% grades are achievable, but this type of driving cycle will push motors in a series system to their peak power and the motors can only maintain peak power for a short amount of time. This indicates that the 60% grade constraint is one of the challenging requirements in the design of a military hybrid vehicle.

2.6 Summary on Military Hybrid Vehicle Research to Date

Many studies have shown that hybrid powertrains can yield fuel economy improvement in varying types of vehicles. A survey of all military hybrid peer reviewed publications illustrates that extensive work has been done with regard to their simulation, optimization and controls. All of the literature focuses on three military vehicles: HMMWV, FMTV and HEMMTT, which span from class III through class VIII. However, there are very few publications with respect to military hybrid vehicle hardware [40, 48, 43], which could be due to cost, proprietary information or the fact that military hybrid vehicle hardware requires more development time than passenger vehicles. Additionally, military vehicles provide unique challenges such as a 60% grade ability, speed on grade, cooling and soft soil mobility.

Many different types of duty cycles were used for the fuel economy investigations. They include time and speed dependent cycles that are defined by the U.S. EPA and distant dependent grade profiles that are defined by the U.S. Army. Both types have duty cycles that represent urban style driving (FUDS, Churchville B) and highway style driving (Federal Highway Cycles, Munson). In addition, some of the publications used a mix so that the fuel economy improvements are reported over a composite duty cycle. While the U.S. Army has tried to define an appropriate military drive cycle, overall there is a lack of an accepted duty cycle to estimate fuel economy improvements such as the FTP 75 used to report miles per gallon for passenger vehicles in the U.S. This could be due to the fact that military threats are constantly changing and it is generally unknown where a military vehicle will be needed.

Fuel economy analyses show that the class III vehicle had the greatest potential for fuel economy improvements over an urban cycle and that those improvements diminish with composite and highway cycles. Heavier vehicles demonstrate the same trend with respect to drive cycles. In some cases there was even a fuel economy degradation over flatter cycles, such as the Munson cycle. In general, heavier vehicles do not show as much fuel economy potential as the class III vehicles. Lastly, fuel economy gains are not the only capability that hybrid system can provide a military vehicle. The hybrid system can be used to provide electrical power for soldiers and allow for an improved noise and thermal signature.

Typically, there is a tradeoff between fuel economy and performance, so it is important to understand the performance constraints, such as acceleration and grade ability. Many of the publications used performance constraints in their analysis, but some did not. Furthermore, the analyses where performance constraints were taken into account used varying constraints. Most notably, the 60% grade ability was omitted from most analysis even though this is a requirement for all military vehicles. Therefore, it becomes increasingly difficult to compare and contrast different conclusions.

In summary, the lack of hardware related research depicts the challenges that a military hybrid vehicle faces. Additionally, the absence of a standard method for understanding the benefit of a military hybrid vehicle makes the cost / benefit relationship impossible to understand. The omission of true performance constraints renders any analysis useless from a military standpoint. Finally, the lack of quantifiable value of "other" capabilities, such as silent watch or V2G connectivity, overlooks the complete advantage that a military hybrid vehicle could provide.

3 Research Objective and Scope

The overall objective of this dissertation is to quantify and understand the complete benefits of a military hybrid vehicle with respect to operational energy. This includes taking into account:

- Propulsion power requirements
- Electrical power requirements for government furnished equipment (GFE)
- Silent watch - defined as the ability to idle and move without the noise and thermal signatures of an internal combustion engine
- Mobile energy exchange
- Mobile energy storage

Understanding the operational energy of a military hybrid allows for a comprehensive, realistic analysis and therefore the benefit of a military hybrid vehicle to be fully quantified. Additionally, it would introduce and explore the novel use of a vehicles as a microgrid that could support a rapid deploying or temporary microgrid. This would not only include developing methods for energy optimization, but creating duty cycles that would represent power demand profiles related to mobile energy exchange and storage.

An unexplored challenge related to this type of analysis will be to coordinate the energy use of the vehicle with stationary microgrids to achieve an overall efficiency. In addition, a military vehicle is used in ways that provide unique challenges, e.g. electrical energy requirements for GFE or idling for lengthy periods of time. This suggests it is beneficial to treat a military hybrid vehicle as a microgrid and utilize energy optimization methods from stationary microgrids, namely SOC optimization. Therefore, the scope of this work will be to detail a process of determining SOC profiles in order to optimize energy use in a military relevant scenario. The next sections will detail this concept, a proof of concept and steps to full realization on a military hybrid vehicle.

4 Conceptual Overview

Figure 7 illustrates typical components of a stationary microgrid as originally defined by Lasseter in reference [7]. It is defined by an energy generator, consumer and storage device. As shown in Figure 7, a generator can be any technology that can feed energy to the grid, a consumer is the user of this energy and the storage device stores excess energy when available and provides energy when necessary or optimal. A supervisory control may be used to oversee the energy transfer, thus ensuring that all requirements are met in the most efficient manner possible. Localized control schemes, such as droop control, can also be used to facilitate power flow.

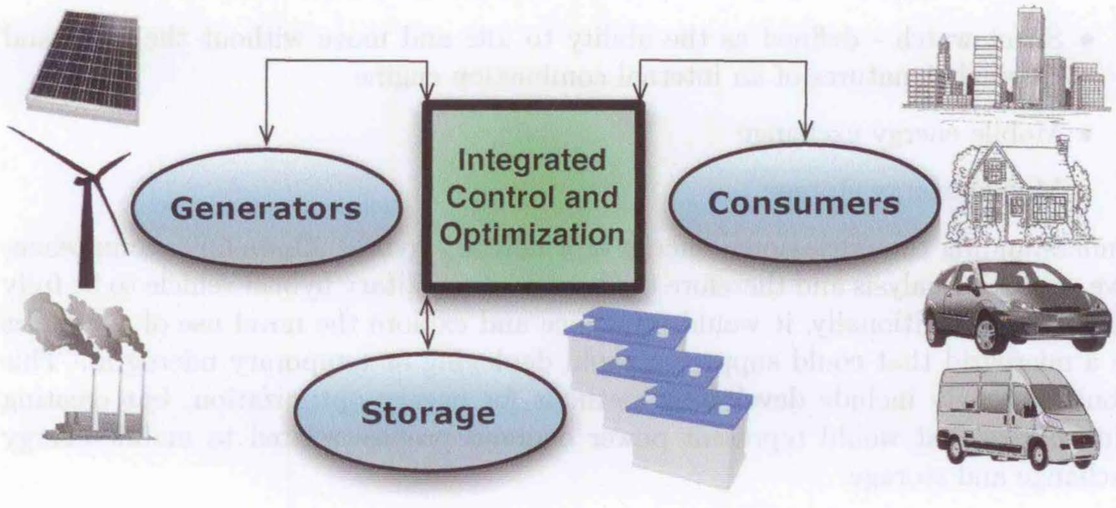

Figure 7: Overview of a generic stationary microgrid

From a military microgrid perspective, it has been shown that SOC control and design optimization can reduce fuel use from 3 to 30%, due to downsized generators and control of renewable energy with a forward looking energy storage strategy [49]. Peters, et al [50] used model predictive control to solve the power dispatch problem for a military microgrid using various prediction horizons. This work also determined that limitations in batteries led to energy waste and the design of microgrids would benefit from more effective control and design of the battery system. The effect of the battery resistance was investigated with respect to voltage and frequency regulation and it was determined that an effective inverter based control design should depend on both regulation and the direct current (DC) source characteristics [51]. Lastly, it was illustrated that a range of plug-in hybrid electric vehicle penetration levels can satisfactorily regulate the voltage and frequency of a military microgrid [52]. In all of this work, storage control and design optimization played a large role.

The concept of a microgrid can be applied on any scale, e.g. a large city or a single building, therefore it should also be applicable to a military ground vehicle as shown in Figure 8. It has a source (typically an internal combustion engine) and consumer (i.e. the propulsion requirement or GFE) and storage (usually a battery of some type). Additionally, it's goal is similar to a microgrid – to fulfill power requirements in the most efficient manner possible. Therefore, the supervisory control of the vehicle would benefit from exploiting methods used to optimize stationary microgrid performance, namely the SOC optimization, which has yet to be explored from a vehicle standpoint.

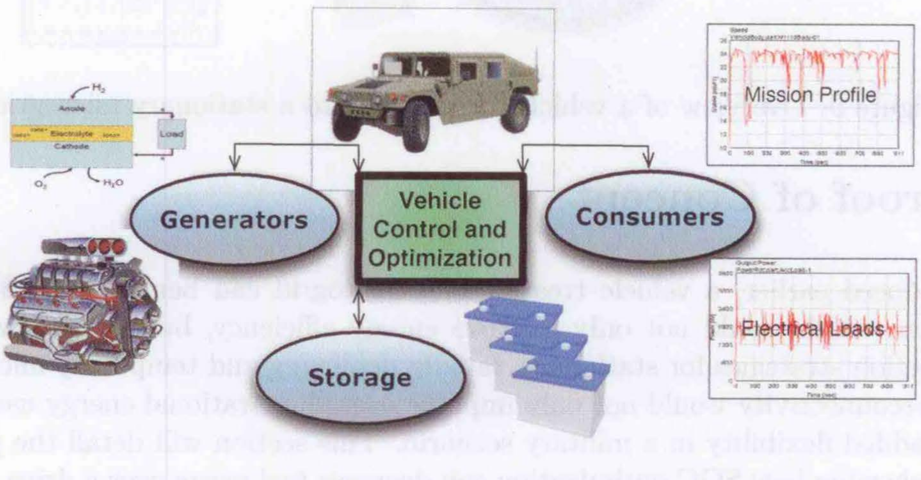

Figure 8: Overview of a vehicle microgrid

This concept becomes increasingly advantageous when the vehicle has the ability to plug into another microgrid and either absorb or provide power; this is described by the term "vehicle-to-grid (V2G) connectivity." As shown in Figure 9, the vehicle now has multiple sources, the engine and the microgrid, and multiple consumers, the propulsion requirements and the microgrid. This capability also allows the military an added security element to temporary connect microgrids via a hybrid vehicle or utilize the vehicles as the sole source for a microgrid in the event a source was removed or unable to provide enough power. Additionally, the power duty cycle related to this type of connectivity related to mobile energy and storage is new research area for military hybrid vehicles.

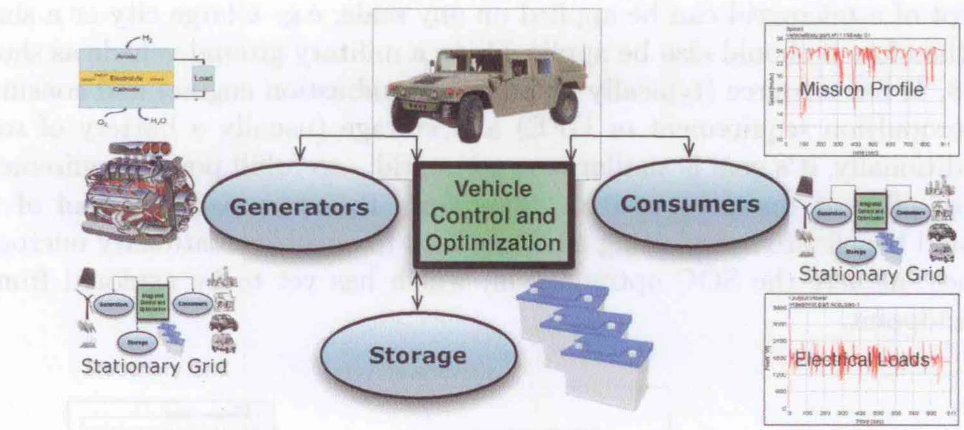

Figure 9: Overview of a vehicle integrated into a stationary microgrid

5 Proof of Concept

As introduced earlier, a vehicle treated as a microgrid can benefit from SOC optimization, which would not only improve energy efficiency, but also allow for interconnection strategies for stationary, rapidly deploying and temporary microgrids. This interconnectivity would not only improve overall operational energy usage, but provide added flexibility in a military scenario. This section will detail the proof of concept showing how SOC optimization can decrease fuel usage over a drive cycle in a hybrid vehicle.

5.1 Hybrid Model

A state space model defined by equations (1), (2) and (3) of a Toyota Prius^{TM} hybrid was shown in [53] and [54], where the inputs were defined as motor torque, engine torque and generator torque. The outputs, or states, were defined as the ring gear or motor speed, which is directly related to the vehicle speed, the engine speed and the battery SOC.

$$\dot{w}_r \left(\frac{\mathrm{I_{vp}}\,(R+S)^2}{\mathrm{I_{ep}}\,K\,R} + \frac{\mathrm{I_{vp}}\,S^2}{\mathrm{I_{gp}}\,K\,R} \right) = \mathrm{T_m} \left(\frac{(R+S)^2}{\mathrm{I_{ep}}\,R} + \frac{S^2}{\mathrm{I_{gp}}\,R} \right) - C \left(\frac{S^2}{\mathrm{I_{gp}}\,K\,R} + \frac{(R+S)^2}{\mathrm{I_{ep}}\,K\,R} \right) + \frac{\mathrm{T_e}\,(R+S)}{\mathrm{I_{ep}}} - \frac{S\,\mathrm{T_g}}{\mathrm{I_g p}} \quad (1)$$

$$\dot{w}_\mathrm{e} \left(R + S + \frac{\mathrm{I_{ep}}\,S^2}{\mathrm{I_{gp}}\,(R+S)} + \frac{\mathrm{I_{ep}}\,K\,R^2}{\mathrm{I_{vp}}\,(R+S)} \right) = \mathrm{T_e} \left(\frac{S^2}{\mathrm{I_{gp}}\,(R+S)} + \frac{K\,R^2}{\mathrm{I_{vp}}\,(R+S)} \right) - \frac{C\,R}{\mathrm{I_{vp}}} - \frac{S\,\mathrm{T_g}}{\mathrm{I_{gp}}} + \frac{K\,R\,\mathrm{T_m}}{\mathrm{I_{vp}}} \quad (2)$$

$$\left(\mathrm{V_{oc}} + \mathrm{C_{batt}}\,S\dot{O}C \right)^2 = \mathrm{V_{oc}}^2 - 4\,\mathrm{R_{batt}} \left(\frac{\mathrm{T_m}\,\mathrm{w_r}}{\mathrm{n_m}^k} + \frac{\mathrm{T_g}\,\mathrm{n_g}^k\,(\mathrm{w_r} - \mathrm{w_e}\,(R+S))}{S} \right) \quad (3)$$

where

$$\begin{aligned}
\mathrm{I_{vp}} &= \mathrm{I_m}\,K + \mathrm{I_r}\,K + \frac{M\,\mathrm{R_{tire}}^2}{K} \\
\mathrm{I_{gp}} &= \mathrm{I_c} + \mathrm{I_g} \\
\mathrm{I_{ep}} &= \mathrm{I_c} + \mathrm{I_e} \\
\mathrm{B} &= \frac{4\,\mathrm{R_{batt}}}{\mathrm{C_{batt}}} \\
\mathrm{C} &= \mathrm{T_{fb}} + M\,\mathrm{R_{tire}}\,\mathrm{f_r}\,g + \frac{0.5\,\mathrm{C_d}\,\mathrm{R_{tire}}^3\,a\,p\,\mathrm{w_r}^2}{K^2}
\end{aligned}$$

and the vehicle constants are defined as:

$S =$ sun gear radius or number of teeth
$R =$ ring gear radius or number of teeth
$K =$ final drive ratio
$M =$ vehicle mass (kg)
$I_M =$ motor inertia $(kg\ m^2)$
$I_r =$ ring gear inertia$(kg\ m^2)$
$I_g =$ generator inertia $(kg\ m^2)$
$I_e =$ engine inertia $(kg\ m^2)$
$I_c =$ carrier gear inertia $(kg\ m^2)$
$T_{fb} =$ braking force$(N\ m)$
$g =$ gravitational force$(\frac{m}{s^2})$
$f_r =$ rolling resistance coefficient
$p =$ density of air (kg/m^3)
$a =$ frontal area (m^3)
$C_d =$ coefficient of drag
$V_{oc} =$ battery open circuit voltage (V)
$n_m =$ efficiency of motor
$n_g =$ efficiency of generator
$R_{batt} =$ battery resistance (Ω)
$C_{batt} =$ battery capacity (Ahr)

However, for this analysis, the vehicle duty cycle or mission profile is known and the goal is to minimize energy use by optimizing SOC. This can be accomplished by constructing a state space representation detailed in equations (4), (5), (6), (7) and (8).

$$\dot{x} = \mathrm{A}\, x + \mathrm{B}\, u \tag{4}$$

$$A = \begin{bmatrix} \frac{R}{\mathrm{I_{ep}}} + \frac{2\,S}{\mathrm{I_{ep}}} + \frac{S^2}{\mathrm{I_{ep}}\,R} + \frac{S^2}{\mathrm{I_{gp}}\,R} & \frac{R}{\mathrm{I_{ep}}} + \frac{S}{\mathrm{I_{ep}}} & -\frac{S}{\mathrm{I_{gp}}} \\ \frac{K\,R}{\mathrm{I_{vp}}} & \frac{S^2}{\mathrm{I_{gp}}\,R+\mathrm{I_{gp}}\,S} + \frac{K\,R^2}{\mathrm{I_{vp}}\,R+\mathrm{I_{vp}}\,S} & -\frac{S}{\mathrm{I_{gp}}} \\ -\frac{4\,\mathrm{R_{batt}}\,\mathrm{w_r}}{\mathrm{n_m}^k} & 0 & 4\,\mathrm{R_{batt}}\,\mathrm{n_g}^k\,\mathrm{w_e} - \frac{4\,\mathrm{R_{batt}}\,\mathrm{n_g}^k\,\mathrm{w_r}}{S} + \frac{4\,R\,\mathrm{R_{batt}}\,\mathrm{n_g}^k\,\mathrm{w_e}}{S} \end{bmatrix} \tag{5}$$

$$b = \begin{bmatrix} \frac{C\,R}{\mathrm{I_{ep}}\,K} + \frac{2\,C\,S}{\mathrm{I_{ep}}\,K} + \frac{C\,S^2}{\mathrm{I_{ep}}\,K\,R} + \frac{C\,S^2}{\mathrm{I_{gp}}\,K\,R} + \frac{\mathrm{I_{vp}}\,R\,\dot{w}_r}{\mathrm{I_{ep}}\,K} + \frac{2\,\mathrm{I_{vp}}\,S\,\dot{w}_r}{\mathrm{I_{ep}}\,K} + \frac{\mathrm{I_{vp}}\,S^2\,\dot{w}_r}{\mathrm{I_{ep}}\,K\,R} + \frac{\mathrm{I_{vp}}\,S^2\,\dot{w}_r}{\mathrm{I_{gp}}\,K\,R} \\ R\,\dot{w}_e + S\,\dot{w}_e + \frac{C\,R}{\mathrm{I_{vp}}} + \frac{\mathrm{I_{ep}}\,S^2\,\dot{w}_e}{\mathrm{I_{gp}}\,R+\mathrm{I_{gp}}\,S} + \frac{\mathrm{I_{ep}}\,K\,R^2\,\dot{w}_e}{\mathrm{I_{vp}}\,R+\mathrm{I_{vp}}\,S} \\ \mathrm{C_{batt}}^2\,\dot{SOC}^2 + 2\,\mathrm{V_{oc}}\,\mathrm{C_{batt}}\,\dot{SOC} \end{bmatrix} \tag{6}$$

$$x = \begin{bmatrix} \mathrm{T_e} \\ \mathrm{T_m} \\ \mathrm{T_g} \end{bmatrix} \tag{7}$$

$$u = \begin{bmatrix} \dot{w}_r \\ \dot{w}_e \\ \dot{SOC} \end{bmatrix} \tag{8}$$

By solving these equations for the engine, motor and generator torque, the total fuel used over the cycle can be determined. Therefore, by inputting ring gear and engine speed, which are derived from the drive cycle, the resultant engine torque can be used to minimize fuel consumption over a drive cycle by optimizing SOC.

5.2 Optimization Problem

Using the hybrid state space model detailed in equations (5), (6), (7) and (8), the following optimization problem (9) was constructed using the fmincon function [55] in MATLAB®.

$$\begin{gathered} \textit{Objective function: minimize } J = \sum_{t=1}^{end} f(\dot{SOC}) \\ \textit{subject to: } 30 \leq SOC \leq 100 \end{gathered} \tag{9}$$

Table 3: Rule based desired engine speed

Rule No.	Vehicle Speed Range (mph)	Engine Speed Setpoint (rpm)
1	0-5	500
2	6-15	900
3	16-30	1500
4	30-55	2000

A drive cycle, shown in Figure 10, which is a plot of time versus vehicle speed, was used as the basis for the inputs into the model. The ring gear speed is directly related to vehicle speed, the engine speed was determined using a rule based control (strategy shown in Table 3) and the generator speed is a function of engine speed. The inputs derived from the drive cycle (Figure 10) are plotted together in Figure 11, which is a plot of time vs. speed for each component.

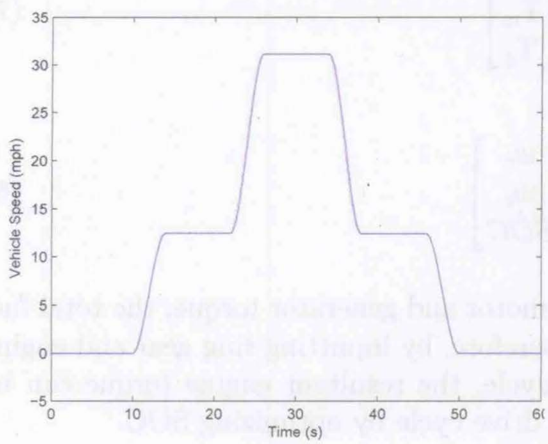

Figure 10: Proof of concept drive cycle

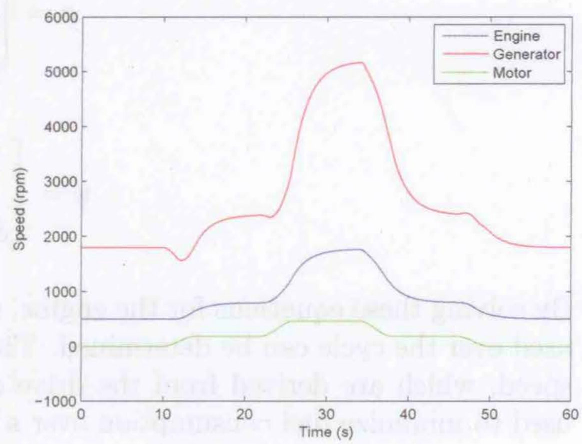

Figure 11: Model inputs

5.3 Define Optimization Parameters

The first step was to determine fuel usage for the case of a constant SOC. For this case, only one SOC level was allowed and a constant SOC of 60% was determined to be optimal. The instantaneous and total fuel usage over the drive cycle are illustrated in Figure 12. This case showed that holding a constant SOC over the input drive cycle will results in a fuel usage of 9.0247 kg.

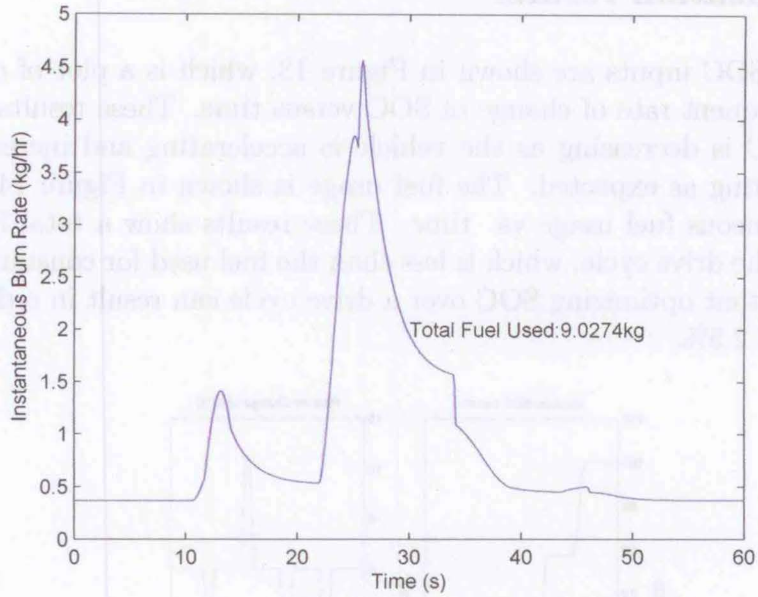

Figure 12: Fuel usage for a constant SOC

The next step was to determine if fuel usage can be minimized by optimizing more than one SOC levels. The number of SOC levels and location of SOC breakpoints were determined by the step changes in the drive cycle; more specifically, the number and location of the zero crossing of the second derivative of the vehicle speed, which is the location of the drive cycle inflection point. This was done problematically using expression (10).

$$\begin{aligned} &\forall\ i : [\text{o} : end] \\ &k = 1, 2, 3 ... end \\ \frac{d^2 mph_i}{dt^2_{mph_i}} * \frac{d^2 mph_{i+1}}{dt^2_{mph_{i+1}}} < 0 \rightarrow\ &\frac{dmph_i}{dt_{mph_i}} = \text{location of local minimum or maximum} \\ &t_{SOC_k} = t_{mph_i} \\ &k = \text{number of SOC levels} \end{aligned} \tag{10}$$

Once the number of SOC levels and locations were determined, these values were used to optimize fuel usage over the drive cycle using fmincon [55] in MATLAB®.

5.4 Optimization results

The optimized SOC inputs are shown in Figure 13, which is a plot of desired SOC levels and subsequent rate of change of SOC versus time. These results depict that the desired SOC is decreasing as the vehicle is accelerating and increasing as the vehicle decelerating as expected. The fuel usage is shown in Figure 14, which is a plot of instantaneous fuel usage vs. time. These results show a total fuel usage of 8.7952 kg over the drive cycle, which is less than the fuel used for constant SOC case. This illustrates that optimizing SOC over a drive cycle can result in reduced energy consumption by 2.5%.

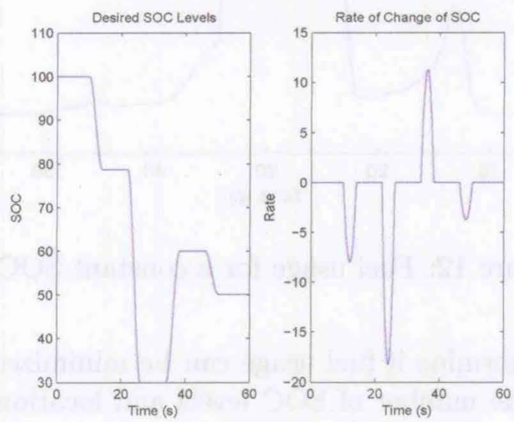

Figure 13: Optimized SOC inputs

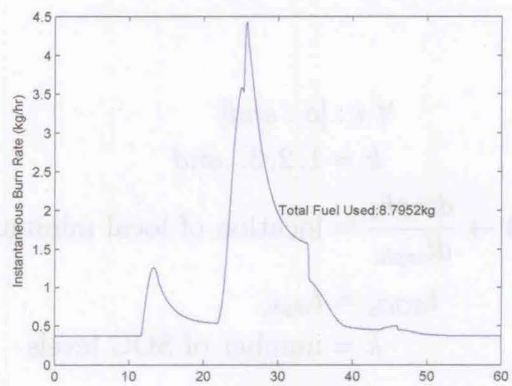

Figure 14: Fuel optimization results

6 Proposed Research

Building on the success of the proof of concept, the following sections will detail the further analysis required to realize the research scope of creating a process to determine an optimal SOC profile to minimize energy. This includes integrating a military relevant cycle, which will require a reduced order optimization method, and a military hybrid model to illustrate robustness in a full military application.

6.1 Military Drive Cycle

While the drive cycle used thus far was justifiable for a proof of concept investigation, it does not represent a realistic military drive cycle. Therefore, the next step will be to integrate a mission profile, such as the plot of time versus vehicle speed for an urban assault mission detailed in [45] and shown in Figure 15. Determining the number of necessary SOC levels and the locations of the SOC break points will become increasingly complex with this type of drive cycle. In addition, rule based engine speed determination could also prove to be challenging. This type of engine speed control will need to be evaluated and the optimization problem may need to contain more than one decision variable, as shown in expression (11).

$$\begin{aligned} \textit{Objective function: minimize } J &= \sum_{t=1}^{end} f(\dot{SOC}, \dot{w}_e) \\ \textit{subject to: } 30 &\leq SOC \leq 100 \\ 0 &\leq w_e \leq 3500 \end{aligned} \tag{11}$$

It is recognized that this method may become computationally impossible. By visual inspection, the urban drive cycle shown in Figure 15 has numerous accelerations and decelerations, which would results in excessive SOC levels. Therefore, a reduced order optimization will be explored.

6.2 Reduced Order Optimization Approach

There are many methods that can reduce the order of a system, which would make the SOC optimization problem more manageable. This section will detail two possible techniques that could be utilized in this approach.

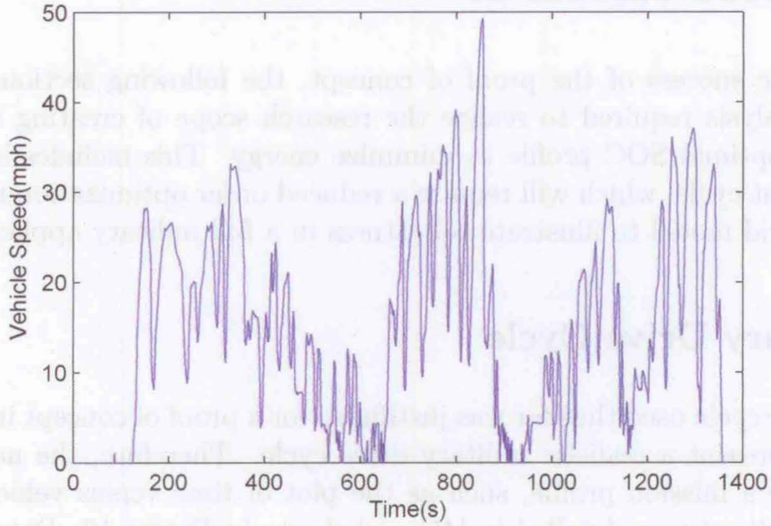

Figure 15: Military duty cycle - urban assault

6.2.1 Proper Orthogonal Decomposition

Proper orthogonal decomposition (POD), also known as principle components analysis, single value decomposition or Karhunen-Loeve transform, dates back to the 1940s for continuous systems [56] and is known for creating a compact representations of complex systems. It has been used to characterize various types of multifaceted systems, as well as for image recognition, signal analysis, and data compression. Two examples of continuous mechanical system modeling can be found in [57] and [58]. In addition, it was shown in [59] a POD can be constructed to represent simulation data created from high order partial differential equations. It is itself an optimization method that minimizes the square distance between the original data set and the reduced linear model. The fundamental concept is that variables can be approximated using expansions with a chosen set of basis functions. This concept is based on the classical projection theorem [60], which is detailed in Theorem 6.1.

Theorem 6.1 (The Classical Projection Theorem) *Let H be a Hilbert space and M a closed space of H. Corresponding to any vector $x \in H$, there is a unique vector $m_0 \in M$ such that $\|x - m_0\| \leq \|x - m\|$ for all $m \in M$. Furthermore, a necessary and sufficient condition that $m_0 \in M$ be the unique minimizing vector is that $x - m_0$ be orthogonal to M.*

The optimization problem would then be described by expression (12):

$$\begin{aligned} \textit{Objective: minimize } J &= \sum_{j=1}^{end} f(SOC) \\ \textit{where: } SOC &= \sum_{j=1}^{N} a_j g_j(\vec{x}) \\ a_j &= \text{scalar} \\ g_j &= \text{orthogonal basis} \\ \vec{x} &= [w_e, T_e] \end{aligned} \tag{12}$$

6.2.2 Volterra Series

Volterra series is a multidimensional combination of a linear convolution and a non-linear power series [61]. It has been successfully used to model non-linear circuits [62], power amplifiers [63], aircraft models [64], loudspeakers [65], unsteady aerodynamics and aeroelasticity [66]. Volterra series can be used to represent continuous or discrete time invariant systems with memory effects from input-output time series data. The discrete system is represented by equation (13) [67].

$$\begin{aligned} y(m) = \sum_{0}^{m} h_1(k)x(m-k) + \sum_{0}^{m}\sum_{0}^{m} h_2 x(m-k_1)x(m-k_2) + \ldots \\ + \sum_{0}^{m} \ldots \sum_{0}^{m} h_n(k_1, \ldots, k_2) \prod_{i=1}^{n} x(m-k_1) + \ldots \end{aligned} \tag{13}$$

$$\begin{aligned} \text{where: } y &= \textit{output} \\ x &= \textit{input} \\ h_n &= \textit{kernels} \end{aligned}$$

Solving for higher order kernels can be complex and computationally challenging. However, Reed et al [68] and Zhu et al [63] have worked to address this problem. This methodology for reduced order optimizations is unexplored from a vehicle energy control perspective. It is also attractive because the kernels or coefficients can be a physical interpretation of a system's response characteristic in the time and frequency domain [66].

6.3 Military Model Verification

A detailed military hybrid vehicle model (shown symbolically in Figure 16) will be used to verify that results translate into a complete military environment. In addition, a second military drive cycle will be used to confirm that the process for determine an optimal SOC profile is robust in a comprehensive military model.

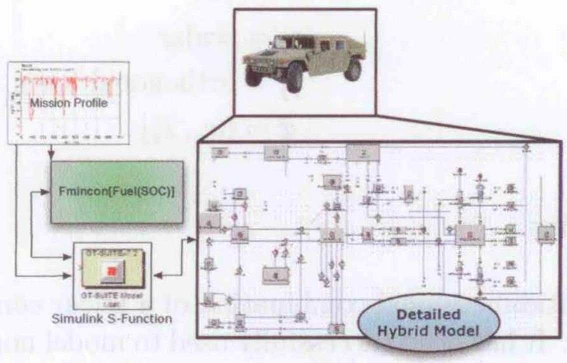

Figure 16: Detailed hybrid model integration overview

7 Impact

This doctoral research project will contribute to understanding military vehicle operational energy by regarding a military hybrid vehicle as a microgrid. This approach of treating the energy sources, consumers and storage devices in a generic fashion and employing existing stationary microgrid control and optimization strategies as well as incorporating appropriate military cycles will allow a holistic view of vehicle energy use to be quantified. In turn, this quantification can be used to better understand the cost/benefit impact of military hybrid vehicles. This knowledge will allow military leaders to identify the optimal powertrain architecture for future vehicles.

In addition to providing thorough insight into vehicle design choices, various other contributions will result from this project. The microgrid analysis of a hybrid military vehicle will aid in the development of interconnection methods in the field of V2G connectivity. Examining V2G connectivity will also allow the development of a rational process for creating optimal SOC profiles, which is a new body of work that will result in an *a priori* optimal control strategy or some type of real-time learning algorithm. Finally, the understanding sensitivity to comprehensive rational military duty cycles will enabled more consistent analyses of energy use related to military hybrid vehicles.

8 Timeline

The timeline for this research is as follows:

1. Military cycle integration: Fall 2012
2. Military hybrid vehicle model verification: Spring 2012
3. Duty cycle sensitivity analysis: Summer 2012
4. Reduced order optimization exploration: Fall 2012

9 Conclusion

Although a large amount of work has been done to show that military hybrid vehicles could improve fuel economy, a military hybrid vehicle has yet to be fielded. This is due to the lack of applicable duty cycles and the absence of military requirements. Therefore, the benefits of a military hybrid vehicle are difficult to translate into a tangible mission energy reduction and vehicles that do not provide military capability are ineffective. Additionally, the full advantage of a military hybrid vehicle has yet to quantified, especially related to microgrids and V2G capability. A hybrid military vehicle can provide support to a rapidly deploying or temporary grid. It could also be the sole source of a stationary grid in the event that the source was not able to meet the demand or if it was removed.

The research objectives of this proposal is to quantify the benefits of a military hybrid vehicle from an operational energy viewpoint. The scope includes considering a military hybrid vehicle as a microgrid to facilitate interconnectivity and exploit current microgrid energy control methods, namely SOC optimization. This is an area of original research that has yet to be explored from a vehicle perspective.

This proposal illustrated that SOC optimization over a drive cycle can improve fuel usage. This work will be extended to include the use of a military relevant drive cycle and be verified with a military hybrid model, which will require the use of a reduced order optimization technique. This work will lead to a rational process of how to determine an optimal SOC profile based on vehicle performance. Additionally, robustness will be verfied with multiple miltiary duty cycles.

This work will allow the understanding of a military hybrid vehicle from an operational energy perspective by quantifying the complete energy use, which will allow a true cost / benefit trade study to be completed.

10 Acknowledgments

The authors would like to acknowledge Mike Pozolo and Gus Khalil of U.S. Army RDECOM-TARDEC, and John Beard of Michigan Technological University, for their insight and feedback into to this work.

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